Invited Paper

The Navy Prototype Optical Interferometer: Recent Developments Since 2004

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ABSTRACT

The technical status of the Navy Prototype Optical Interferometer (NPOI) since the last SPIE meeting is summarized along with the current science programs. The instrument is operated in an automatic observational mode, obtaining over 10,000 stellar observations in the period, June 2004 through March 2006. The scientific program has been directed at astrometry, TPF candidate stars, binary stars and other interesting targets such as Be stars. A significant database of NPOI observations obtained in 1997-2004 is being analyzed for binaries and single stars such as rapid rotating stars: Altair and Vega.

I. Description of the Instrument

The NPOI, Armstrong et al.[1] located on Anderson Mesa, AZ, is a joint project of the U. S. Naval Observatory and the Naval Research Laboratory in cooperation with Lowell Observatory. The NPOI includes arrays for both imaging and astrometry. The imaging array (when completed) will consist of six movable 50-cm siderostats feeding 12-cm apertures, with baseline lengths from 2 m to 437 m. Currently two imaging siderostats are in operation, which in conjunction with the astrometric array provide baselines up to 79 m. The astrometric array consists of four fixed 50-cm siderostats feeding 12-cm apertures (soon to be increased to 35 cm by the addition of beam compressors), with baseline lengths from 19 m to 38 m. The astrometric array also includes extensive laser metrology to monitor the positions of the stations and the internal starlight paths during astrometric observations. The arrays share vacuum feed and delay line systems. The NPOI features rapid tip-tilt star tracking, active group-delay fringe tracking over a wide band (currently 550 - 850 nm in 16 channels, soon to be upgraded to 450 - 850 nm in 32 channels), and a high degree of operational automation. The NPOI is currently the world's only long-baseline optical interferometer capable of simultaneously co-phasing up to six elements, Hummel et al.[2]. The wide detection bandwidth and rapid observing duty cycle of the NPOI make rapid surveys and snapshot imaging practical.

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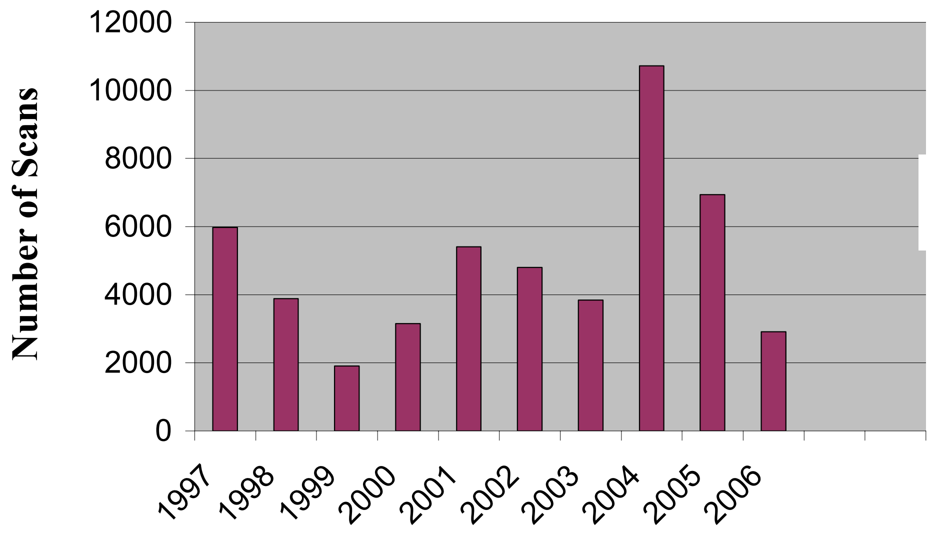


Figure 1. The number of scans obtained with the NPOI from January 1997 to April 2006. Three way beam combination began in 1996 and six way beam combination in 2002.

The instrument is scheduled for observations every night. Since one of the major programs of the NPOI is wide angle astrometry, it has always been emphasized that a large number of observations be obtained on each observing night. This is to allow for a reasonable solution on nights of astrometric measurements. Figure 1 displays the number of scan obtained between 1997 and April 2006. The decrease in scans between 1998 and 2001 is due to contamination of the optics due to a vacuum leak in the beam transport system. The large number of scans in 2004 is due to especially good weather.

In the 22 months since the last SPIE meeting 13,979 multi-baseline scans were obtained in 348 nights, an average of 80 scans per night. The scan length is 30 seconds. The faintest objects reliably observed (fringe tracking limit) correspond to a V magnitude limit of 6.1. The maximum number of multi-baseline observations in one night is 275.

II. Improvements Since Last SPIE Meeting

Since the last SPIE meeting in June 2004, the following improvements have been made.

Wide-angle astrometry:

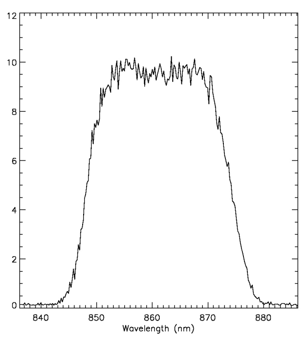
- A constant-term metrology system was completed for all 4 astrometric stations to monitor internal optical paths from the beam combiner room to the siderostats.

- The constant-term metrology, with calibration by white light and baseline metrology, was shown to substantially reduce astrometry residuals.

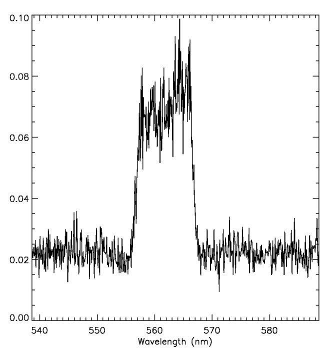
- Narrow-band HeNe rejection filters were added.

FTS mode for routine use:

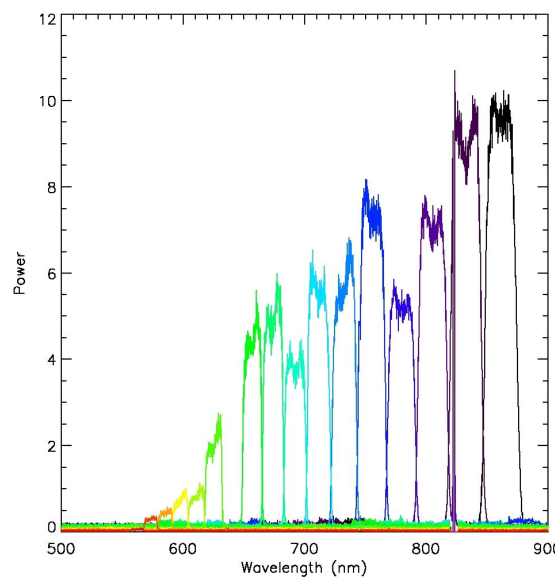
Regular Fourier Transform Spectrometer (FTS) scans are taken during cloudy nights, and daytime calibration runs, to monitor the alignment and potential drifts of the NPOI's spectral channels. The internal accuracy is 0.1 nm with a repeatability of 0.5 nm. Figure 2 shows the resulting channels. Note that channel 16 is very low due to sampling and the spectral response of the white light source. The astrometric observations require a precise wavelength scale to calibrate the atmospheric dispersion and delay.



Channel 1



Channel 16



Spectral Channels

Figure 2: Spectral channels from FTS measurements. The bandpasses for channels 1 and 16 are also shown.

Further, observations of wide binary systems also require that we account for bandwidth smearing at wide (100mas or more) separations. Bandwidth smearing reduces the fringe visibility at wide separations, and proper correction for this effect requires knowledge of the centers and widths of the spectral channels. Precise sub-nanometer measurements of the NPOI's channel widths and centers are required for a proper modeling of the effects of bandwidth smearing on the observed visibilities. Analysis of systems like Gamma Virginis (separation ~ 600 mas) and Zeta Herculis (sep ~ 800 mas) would be impossible

without the information provided from the FTS results. At such large separations bandwidth smearing reduces observed squared visibilities by as much as 50%.

Miscellaneous developments since last SPIE meeting:

- Software has been completed to allow rapid system reconfiguration. Station reconfiguration can be done by the observer on demand during a night and spectrometer reconfiguration can be done daily.

- Basic NPOI reduction pipeline (NRP) package finished.

- Siderostat at E02 moved to E06, providing a new 79 m baseline now in regular use.

- A new observation planning tool, "Obsprep," was developed.

- Gate valve stands will soon be completed on the array vacuum feed beam tubes.

III Scientific Programs

IIIa. Astrometry

The present efforts are focused on reducing the data from a recent astrometric observation run. We are in the process of applying corrections due to siderostat axis offsets, mirror offsets and thermal motion of the siderostats to the astrometric delay residuals. Figure 3 shows typical motion, as measured by a siderostat's 5-beam metrology system, of a cats-eye. Ideally the siderostat axes would intersect at a point and the cats-eye would be mounted at exactly the intersection point. For a real mechanical siderostat, there is a finite displacement between the axes and between the cats-eye and elevation axis. The motion of the cats-eye is due to these displacements and thermal motion of the siderostat. Milliarcsecond astrometry requires that these motions be correctly modeled and accounted at the submicron level.

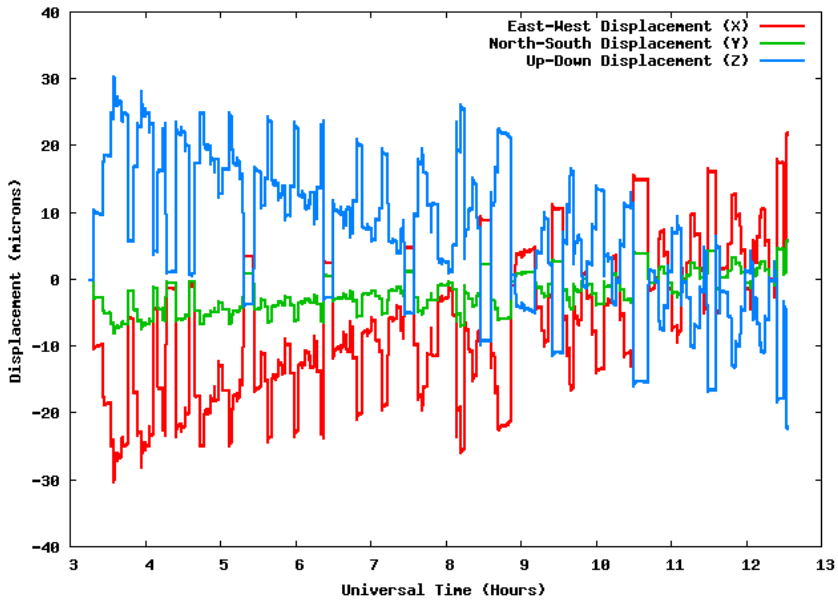


Figure 3. Measured Cat's eye displacement during observations as measured by the siderostat's 5-beam metrology system.

IIIb. TPF survey

We selected 101 potential TPF target stars (V magnitude < 4.3, declination north of −20 degrees) for observations by the NPOI. We have analyzed observations of 31 of the 50 targets observed in our first campaign. At present there is no evidence for unknown stellar companions in any of the 31 stars we have analyzed, to a current limiting Δm of 2.8 with separations of 3 mas to 1000 mas. Five of the stars were found to be larger than 3 mas and an estimate can be made of their diameters to 3%.

As part of a multiplicity survey of potential Terrestrial Planet Finder (TPF) target stars we observed known binaries of varying Δm and separation. These observations used baselines of 18.9 and 22.2 meters, in a simple two baseline setup to maximize our observing efficiency. Fig. 4 shows the results of these "Δm and separation" tests. The NPOI's binary dynamic range with only 20 meter baselines extends from separations of 3 mas to 800 mas, and to a V band magnitude difference of 2.8. Although the NPOI excels at resolving close binaries, this plot demonstrates that we can overlap with the capabilities of speckle interferometry. Such an overlap is essential in the study of high eccentricity systems.

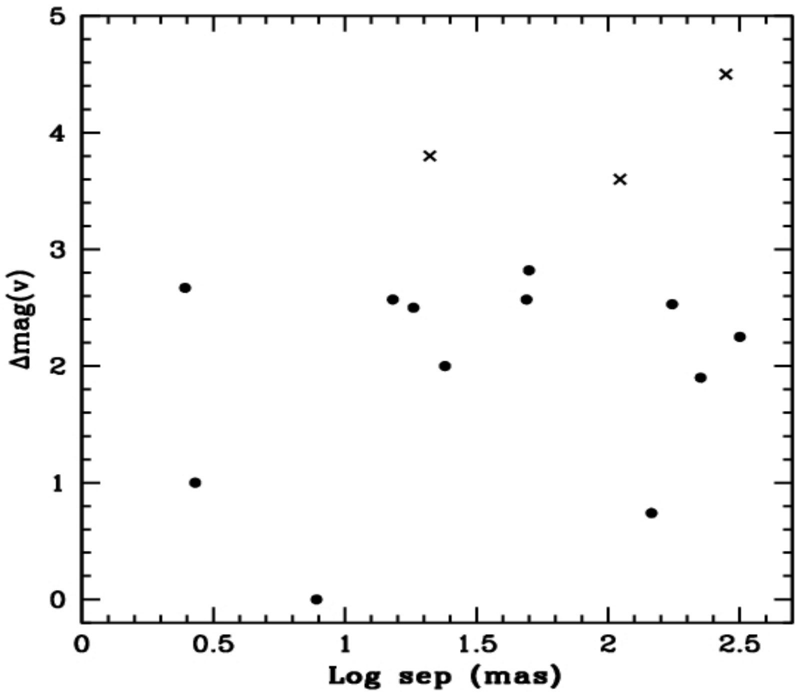


Figure 4: Sensitivity in detecting binary stars. Separation as large as 800 mas can be detected after accounting for bandwidth smearing but are not shown for clarity. ● are detections, **x** are non-detections.

IIIc. Binary star studies

Binary star observations with the NPOI can be very efficient, obtaining precise relative astrometry with just a few scans. Figure 5 shows an image made of the Δm = 2.57 binary Phi Herculis at a separation of 15 mas, Zavala et al.[3]. The accompanying *u,v*-coverage plot in Figure 5 shows the *u,v* coverage obtained with the NPOI's longest 79 meter baseline, and that a brief three-scan (90 seconds total integration time) observation can produce relatively high dynamic range images of simple sources. The detection of previously unseen companion in this single-line HgMn spectroscopic binary predicts that the secondary is A8V, which has been subsequently confirmed by spectroscopic observations.

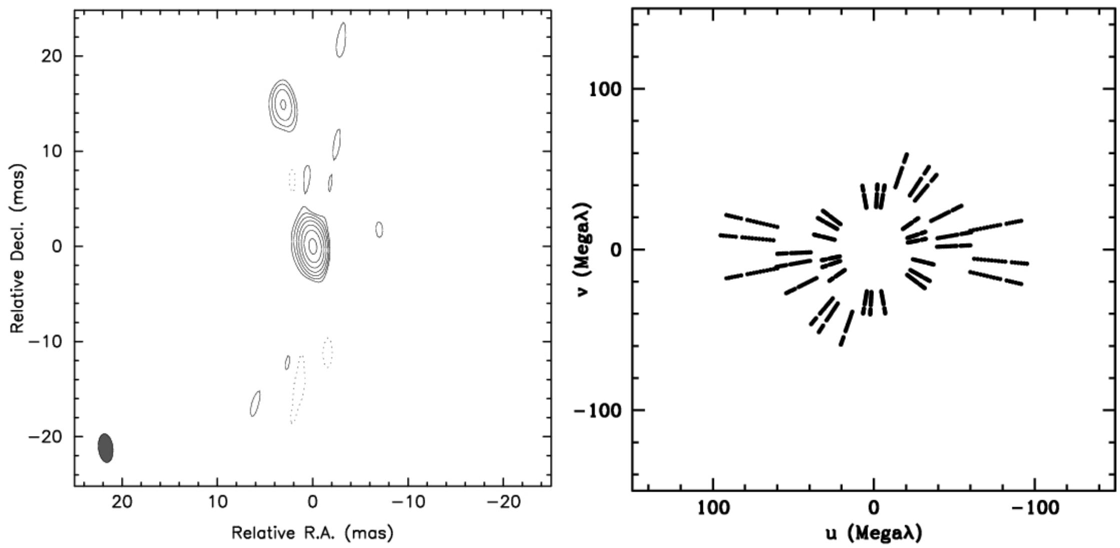


Figure 5: Image of Phi Her made with three scans, and the *u,v* coverage for this image.

There is beginning to be a substantial amount of long baseline interferometric data on bright binaries. This data together with radial velocity measurements is now making substantial contributions to stellar astrophysics. From a reanalysis of Mark III data obtained on thirty nights in 1989-1991 and four nights obtained with the NPOI in 1997-1998, together with orbits obtained from radial velocity measurements, Armstrong et al.[4] have characterized the components of the Hyades binary Theta 2 Tau. From the interferometer data and the Hipparcos parallax, the total mass of the system is 4.03 ± 0.20 solar masses. The best spectroscopic orbits then produces individual masses of 2.15 ± 0.12 and 1.87 ± 0.11 solar masses. The Hipparcos parallax and the Δm of 1.13 ± 0.05 from the interferometry produce the absolute visual magnitudes of 0.48 ± 0.05 and 1.61 ± 0.06. These results pose problems for stellar evolution models. No single isochrone based on current estimates of the helium content and metallicity of the Hyades fits both components (see Figure 6).

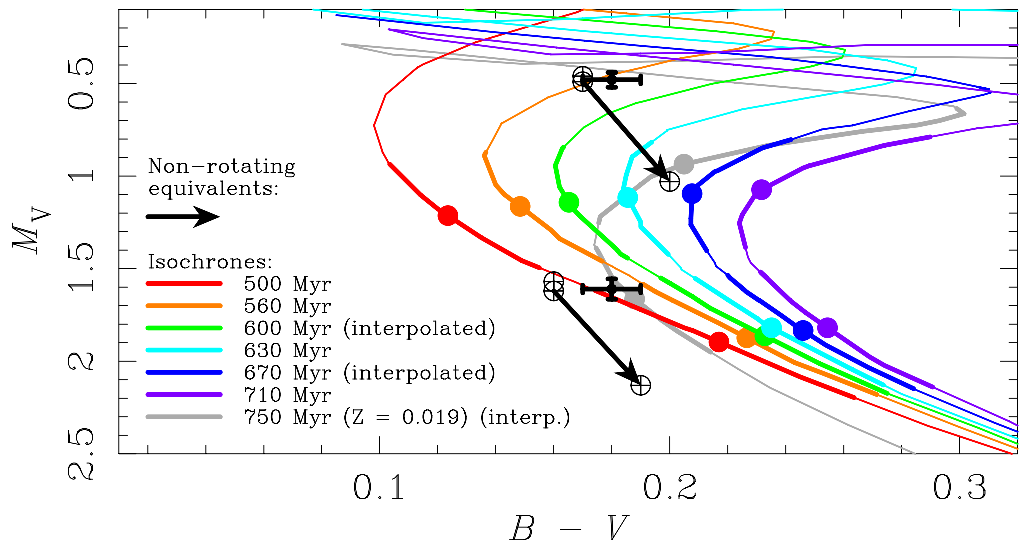


Figure 6: Components of Theta 2 Tau compared with isochrones of Girardi et al.[5]. Thicker portions mark the ±1σ mass ranges; black error bars are the observed magnitudes and colors; circles with crosses mark the magnitudes and colors of non-rotating stars of the same mass and luminosity, as seen from three inclination angles.

IIId. Be stars

We have observed 14 Be stars in the H-alpha line and the continuum, including Phi Her, Gamma Cas, Delta Sco, and Kappa Dra. Observations of Eta Tau and Beta CMi, combined with older data from the literature, were used to demonstrate dependence of H-alpha emission on the linear size of the emitting region, consistent with optically thick line emission that is proportional to the effective area of the emitting disk, Tycner et al.[6]. Narrow-band filter observations have been successful in increasing the contrast with the stellar continuum. 64-m baseline measurements (Figure 7) demonstrated that a Gaussian disk model is superior to a uniform disk or a ring in fitting the H-alpha emission from Gamma Cas. Interferometric observations combined with spectroscopy allow the same determination to be made for Phi Per as well, Tycner et al.[7].

Binary stars are well known as the source for precise determinations of stellar masses, but their application goes far beyond that important task. Close binary stars resolved by optical interferometry, are also an important source of information for stellar disks and interaction processes between stellar companions. The Be star Delta Sco is an excellent case in point. As a typical Be star Delta Sco possesses a circumstellar disk, which is produced not from accretion but from material removed from a rapidly rotating B star. Delta Sco is also a highly eccentric (e = 0.9) binary with Δm = 2.2. Observations of Delta Sco using the NPOI's H-alpha setup, Tycner et al.[7], show that the circumstellar disk is approximately 3 mas in size. That puts the disk very close to the periastron point. Thus, Delta Sco is a prime candidate to test models for disk disruption by stellar companions, and to observe a possible stellar collision with the circumstellar disk.

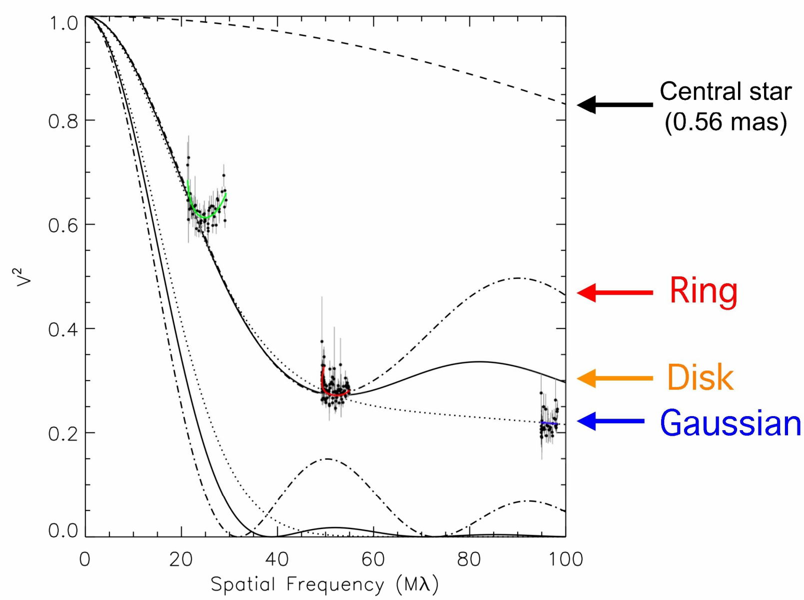


Figure 7: H-alpha V^2 data for Gamma Cas. The 64-m baseline data at 100 Mλ show that a Gaussian disk is the best model for the disk.

IIIe. Rapid Rotators:

Rapidly rotating stars display an asymmetric brightness distribution. Observations have been made of Vega, Altair, Regulus and Zeta Oph. Peterson et al.[8], in a reanalysis of earlier observations, have shown the rapidly rotating star Vega to be seen almost pole on with an inclination of 4.5 degrees rotating at 93% of breakup velocity.

IIIf. Other programs

1. Binaries observed for orbit determination/improvement, "imaging," or planet search experiments: ~24 (e.g., Beta CrB, Phi Her, Theta 1 Tau)

2. Solar analogs (diameters): ~12 stars

3. Irregular variable star: Rho Cas

4. S Star: BD Cam

5. Star with extra-solar planet: Tau Boo

6. Cepheids: Ex: Zeta Gem, Eta Aql

7. Wide-angle astrometry: 32 stars (many nights each)

8. "Medium-angle" astrometry: 5 stars with separations 1 to 10 degrees

9. Calibration experiments: ~9 stars

10. Binaries at large Δm: ~7 systems

IV. Summary

The NPOI has concentrated on filling out the inner part of array in the past two years. Future work will be aimed at establishing a catalog of bright star positions and continuing the observational programs on stellar emission on the surfaces of stars and their circumstellar environment as well as studies of binary stars for precise mass determination. The existing databases from the Mark III and NPOI interferometers will continue to be analyzed for scientific research. Technically the available aperture will be expensed from 12 cm to > 30 cm and the baseline lengths will be extended out to 430 m.

REFERENCES

1. Armstrong, J. T.; Mozurkewich, D.; Rickard, L. J.; Hutter, D. J.; Benson, J. A.; Bowers, P. F.; Elias, N. M., II; Hummel, C. A.; Johnston, K. J.; Buscher, D. F.; Clark, J. H., III; Ha, L.; Ling, L.-C.; White, N. M.; Simon, R. S., ApJ, 496, 550, 1998.
2. Hummel, C. A.; Benson, J. A.; Hutter, D. J.; Johnston, K. J.; Mozurkewich, D.; Armstrong, J. T.; Hindsley, R. B.; Gilbreath, G. C.; Rickard, L. J.; White, N. M., AJ, 125, 2630, 2003.
3. Zavala, R.T., Adelman, S.J., Hummel, C.A., Gulliver, A.F., Caliskan, H., Armstrong, J.T., Benson, J.A., Hutter, D.J., Johnston, K.J., and Pauls, T.A., ApJ, submitted, 2006.
4. Armstrong, J. T.; Mozurkewich, D.; Hajian, Arsen R.; Johnston, K. J.; Thessin, R. N.; Peterson, Deane M.; Hummel, C. A.; Gilbreath, G. C., AJ, 131, 2643, 2006.
5. Girardi, L., et al, A&AS, 141, 371, 2000.
6. Tycner, Christopher; Hajian, Arsen R.; Armstrong, J. T.; Benson, J. A.; Gilbreath, G. C.; Hutter, D. J.; Lester, John B.; Mozurkewich, D.; Pauls, T. A., AJ, 127, 1194, 2004.
7. Tycner, Christopher; Gilbreath, G. C.; Zavala, R. T.; Armstrong, J. T.; Benson, J. A.; Hajian, Arsen R.; Hutter, D. J.; Jones, C. E.; Pauls, T. A.; White, N. M., AJ, 131, 2710, 2006.
8. Peterson, D. M.; Hummel, C. A.; Pauls, T. A.; Armstrong, J. T.; Benson, J. A.; Gilbreath, G. C.; Hindsley, R. B.; Hutter, D. J.; Johnston, K. J.; Mozurkewich, D.; Schmitt, H. R., Nature, 440, 896, 2006.